Determining Stability Margins in Adiabatic Superconducting Magnets with 3-D Finite Element Analysis

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Outline

- Background
  - Superconductivity
  - Quench and MQE
  - Why MQE is useful
- Calculation approach
- ANSYS simulation
  - Why we need it
  - How we need it
  - How it works
- Results
- Conclusions
- What's next?

What is superconductivity?

- Is a phenomenon where a material exhibits zero electrical resistivity at very low temperatures.
- Was discovered in mercury in 1911 by Heike Kamerlingh Onnes.
- Many other materials afterwards have been discovered to be superconducting.


Kamerlingh Onnes
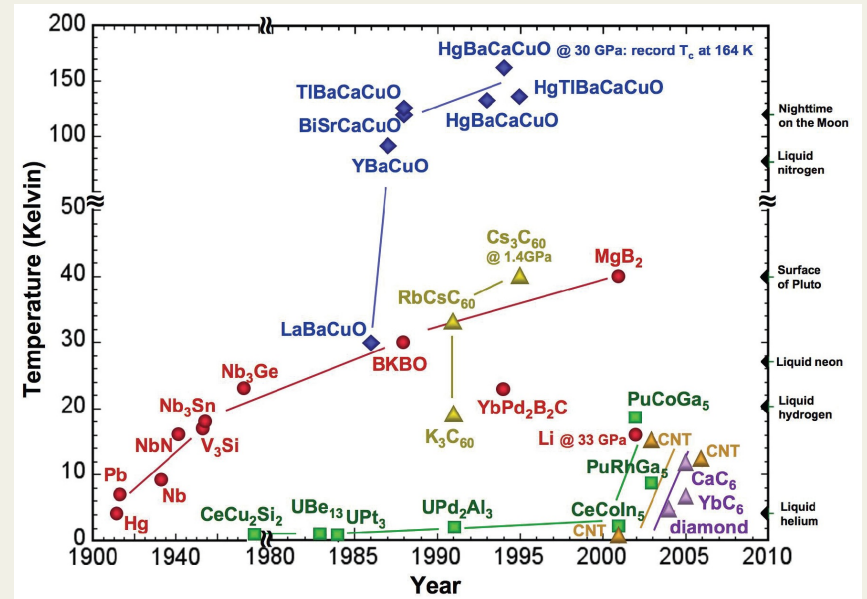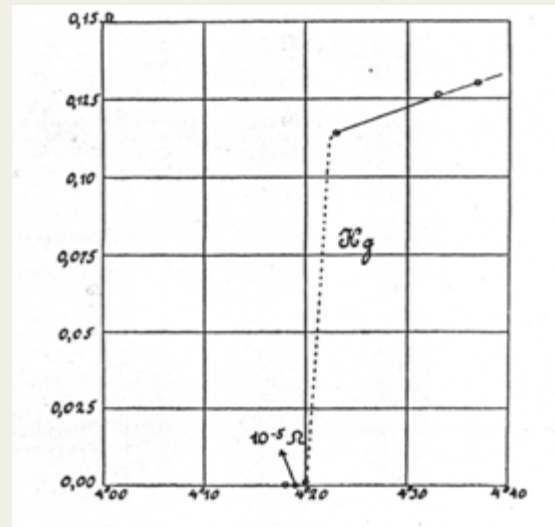
Why do we study superconducting magnets at Fermilab?

- Fermilab pioneered their use, and continues to use them for a variety of purposes.

- Dipole magnets for beam bending, quadrupoles for beam focusing, solenoids for detectors, etc.

- Superconducting magnet applications branch out: Tevatron tech directly led to MRI's.

What is quench and why should we worry about it?

- Quench occurs when a small section of the superconductor becomes normally resistive.

- This normal zone generates Joule heating, which expands the normal zone.

- This can damage expensive equipment and render magnets unusable. (Thermal strain, high internal voltage)
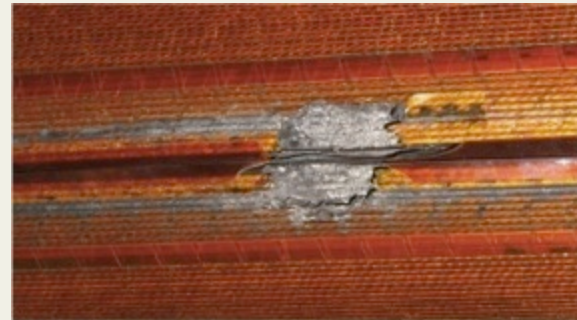
A meltdown in an LHC main bending magnet due to a quench

J. Schwerg, PhD thesis, 2010

An example of quench:
- I_o=160 A (70% I_c), 37 K
- YBCO superconductor
- Conduction-cooled, nearly-adiabatic situation
- T_{peak}= 450 K in 2 sec
- 50% I_c degradation

Mbaruku et al., IEEE Trans. Appl. Supercond. **17** 3044, (2007)

How does quench happen?

- Initial energy input into the magnet
- Wire movement, epoxy cracking, etc.
- $\Delta Q \rightarrow \Delta T$
- If ΔT makes operating current $>$ Ic, current flows proportionally out of the superconductor and into the matrix, causing heating due to current sharing.
- In fully normal sections of the magnet, current flows entirely through the matrix.
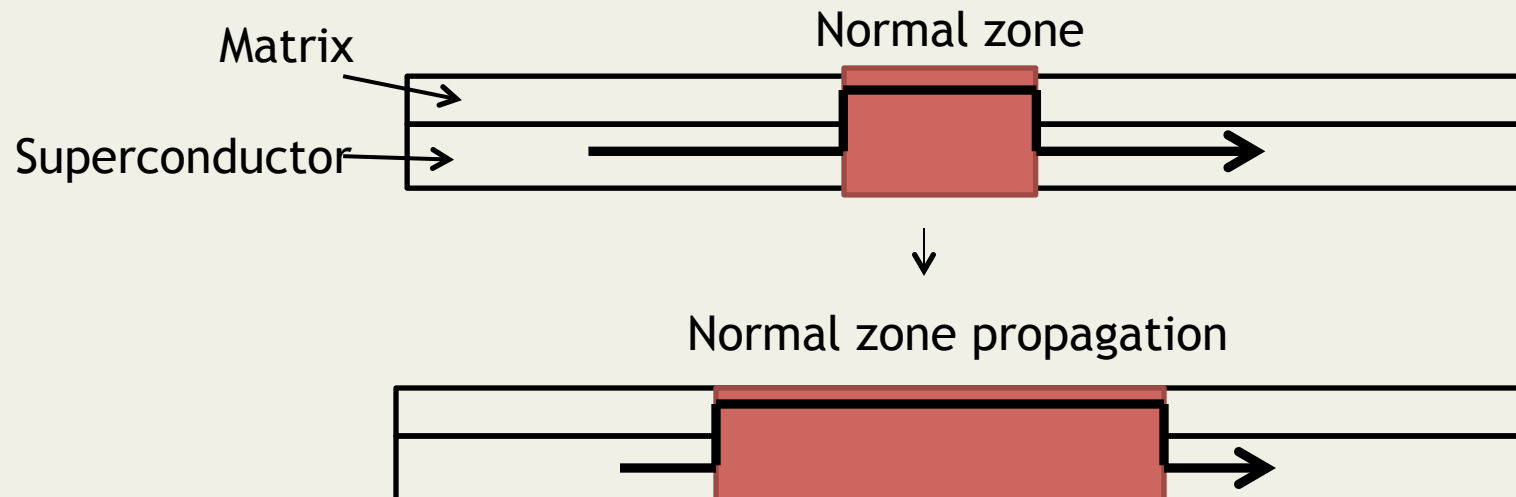
What is MQE and how is it useful?

- The minimum quench energy (MQE) is the minimum heat energy ΔQ needed to start a quench.

- The minimum quench energy depends on a lot of things, but is mainly influenced by the operating current and the conductor's material properties.

- It is a very important engineering parameter to determine cryostability in the magnet.

- Finding the MQE for different operating currents allows us to plot the cryostability of the magnet as a function of its operating current.

Predicting thermal behavior: the MIITS method

$$C(T)\frac{\partial T}{\partial t} = \nabla \cdot (k \cdot \nabla T) + J^2 \cdot \rho + \frac{Qini}{V}$$

Heat absorption by the material

Thermal conduction

Joule heating

Initial heat pulse

Assuming the initial heat input is minimal and ignoring cooling/conduction:

$$J_m^2 \rho(T)dt = C(T)dT$$

Depends on operating current and time span

$$\int_0^\infty J_m^2(t)dt = J_m^2 t_p = \int_{T_0}^{T_m} \frac{C(\theta)}{\rho(\theta)}d\theta = Z(T_m,0)$$

Only depends on material properties

MIITS predictions

- A program in MATLAB was developed that exploited this approach to calculate hot spot temperature as a function of time.
- This is also a very important engineering consideration in magnets.

Predicted maximum hot spot temperatures for different operating current modes vs. time
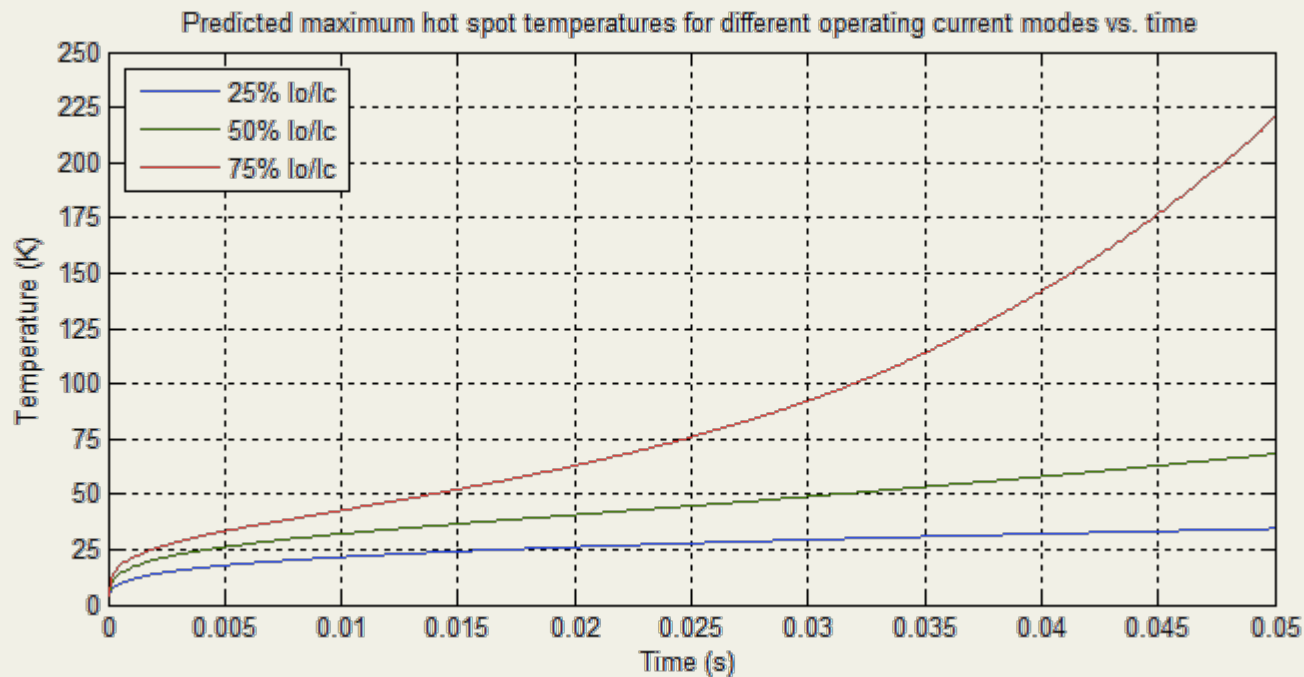
Why is FEA simulation required?

- The previously presented method does not incorporate thermal conductivity or current sharing behavior.

- It also assumes the magnet composition is homogeneous.

- This method cannot determine other important stability parameters like MQE and normal zone propagation velocity.

How a finite element analysis simulation is required

- To calculate MQE as a function of operating current, multiple runs must be performed to obtain one result, and then the conductor conditions must be changed to obtain another.

- The objective is to make the program as flexible as possible: the conductor should be customizable.

- Data output should have a reasonable time frame: full data should be ready in a workday.

Accuracy

Flexibility

Time-efficiency
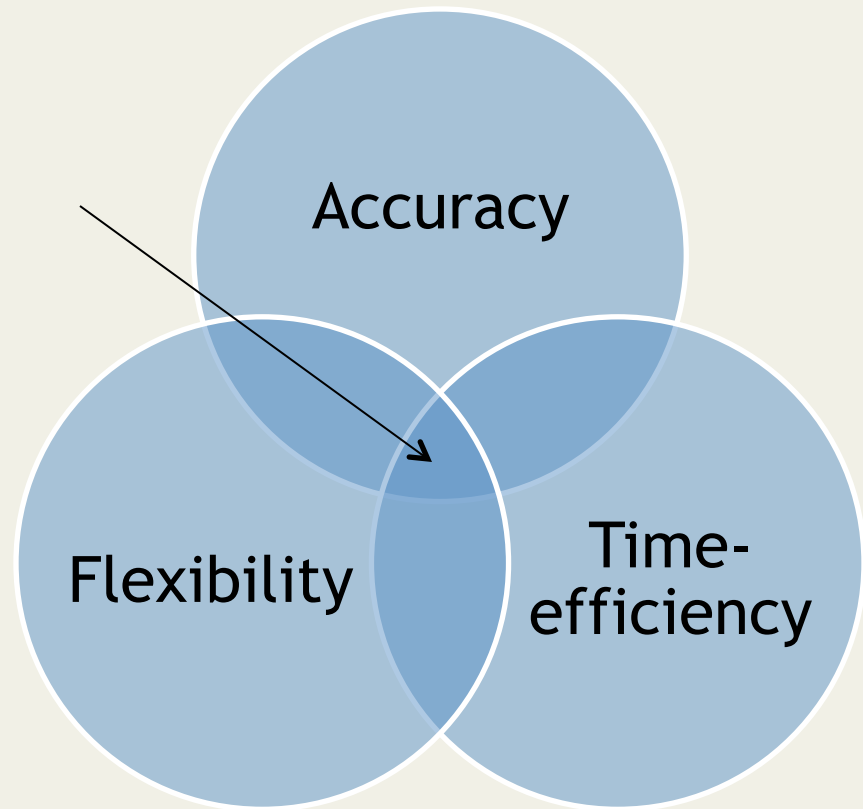
How it works: pre-solving

- The pre-solving method is almost entirely parametric: solution process depends only on material identifiers and node positions.

- Material properties, operating conditions and geometry can be altered with minimal code alteration by users.

- This allows for testing of different materials and geometries, like high-temperature superconductors and multiple strands.

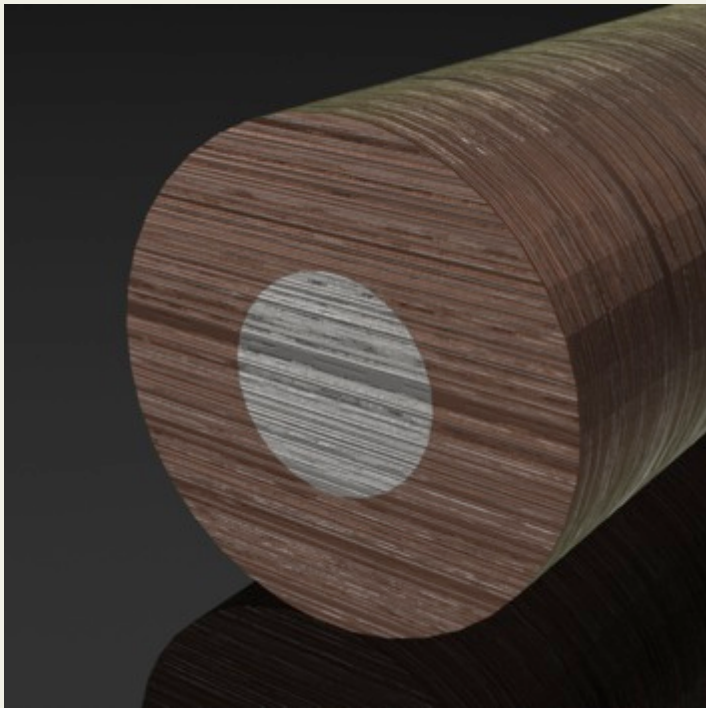- The sole requirement is that nodes be located regularly along z-axis.
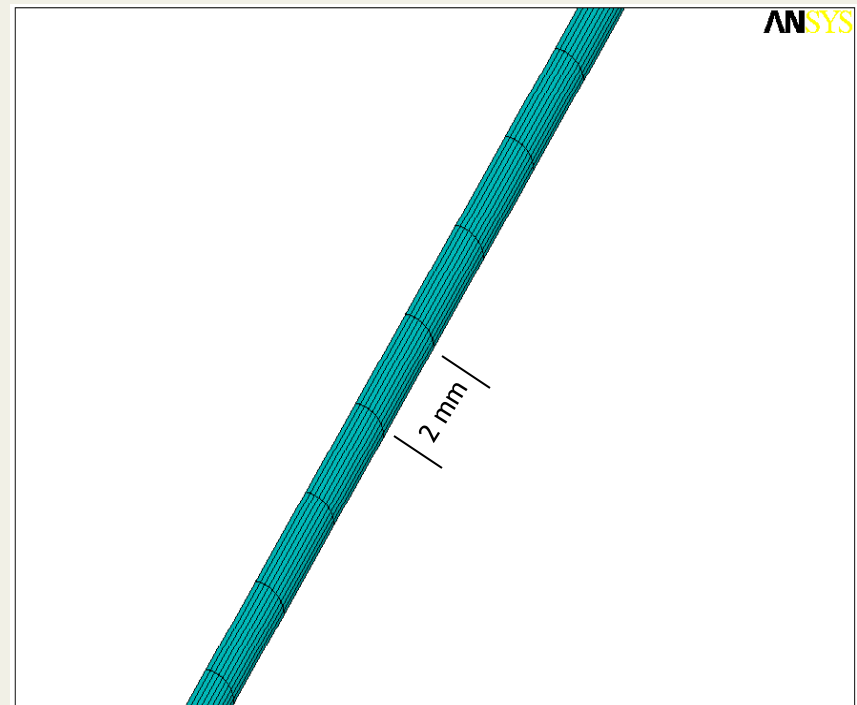
How it works: solving
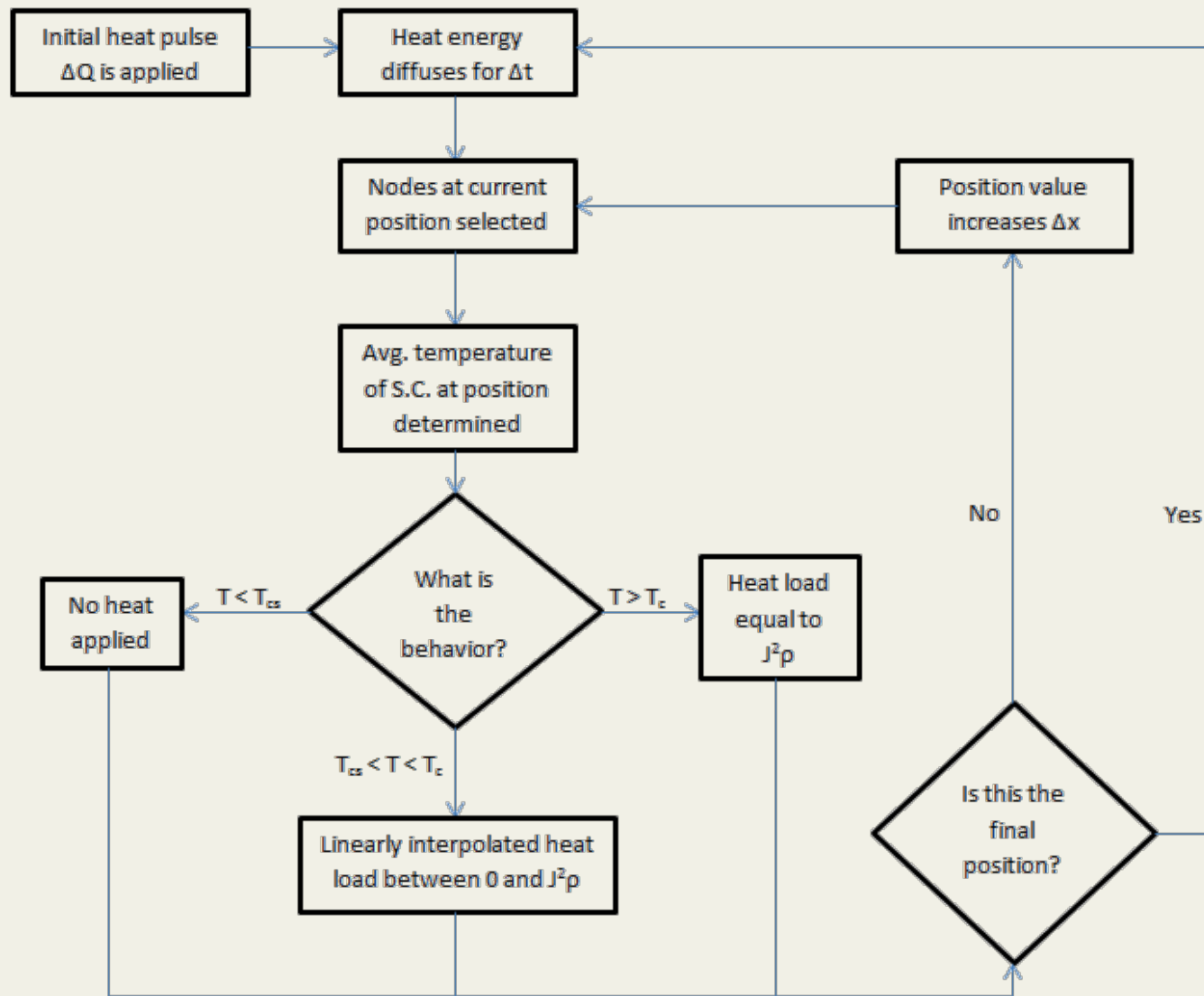
Simulated cases

- Single-strand case
- NbTi superconductor, Cu matrix, no coolant
- All thermal energy stays in the strand
- Good for comparisons and material testing since no heat energy is lost

- Multi-strand case
- NbTi superconductor, Cu matrix, G-10 insulator, no coolant
- Thermal energy doesn't stay in strands
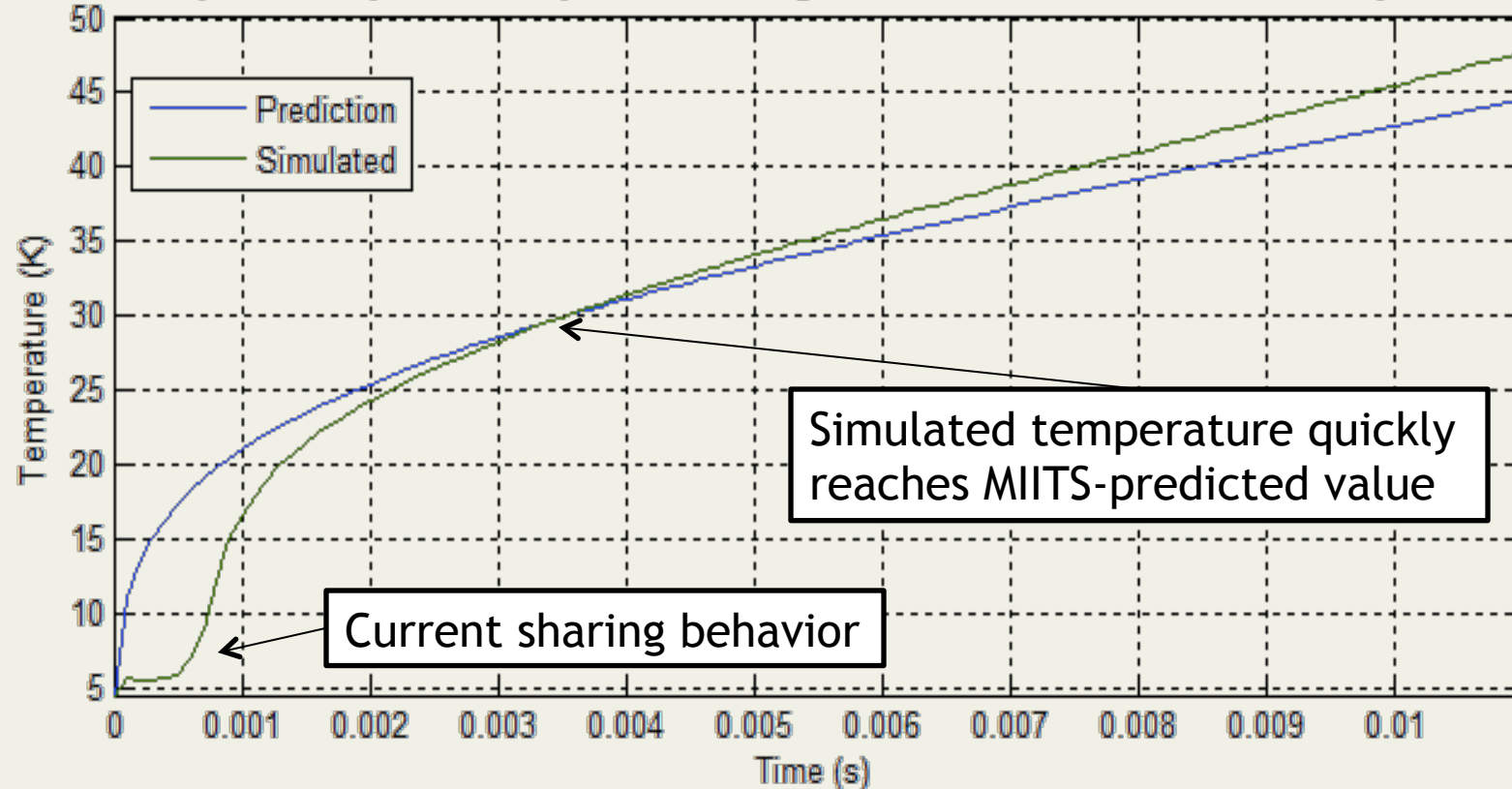- Good for insulation tests and geometry optimization; reflects usage conditions
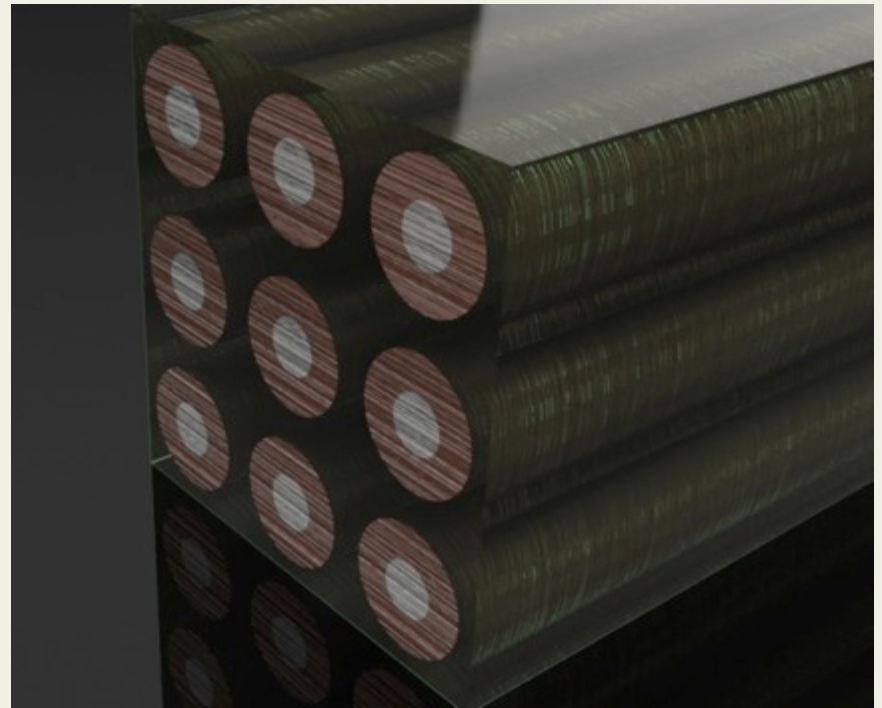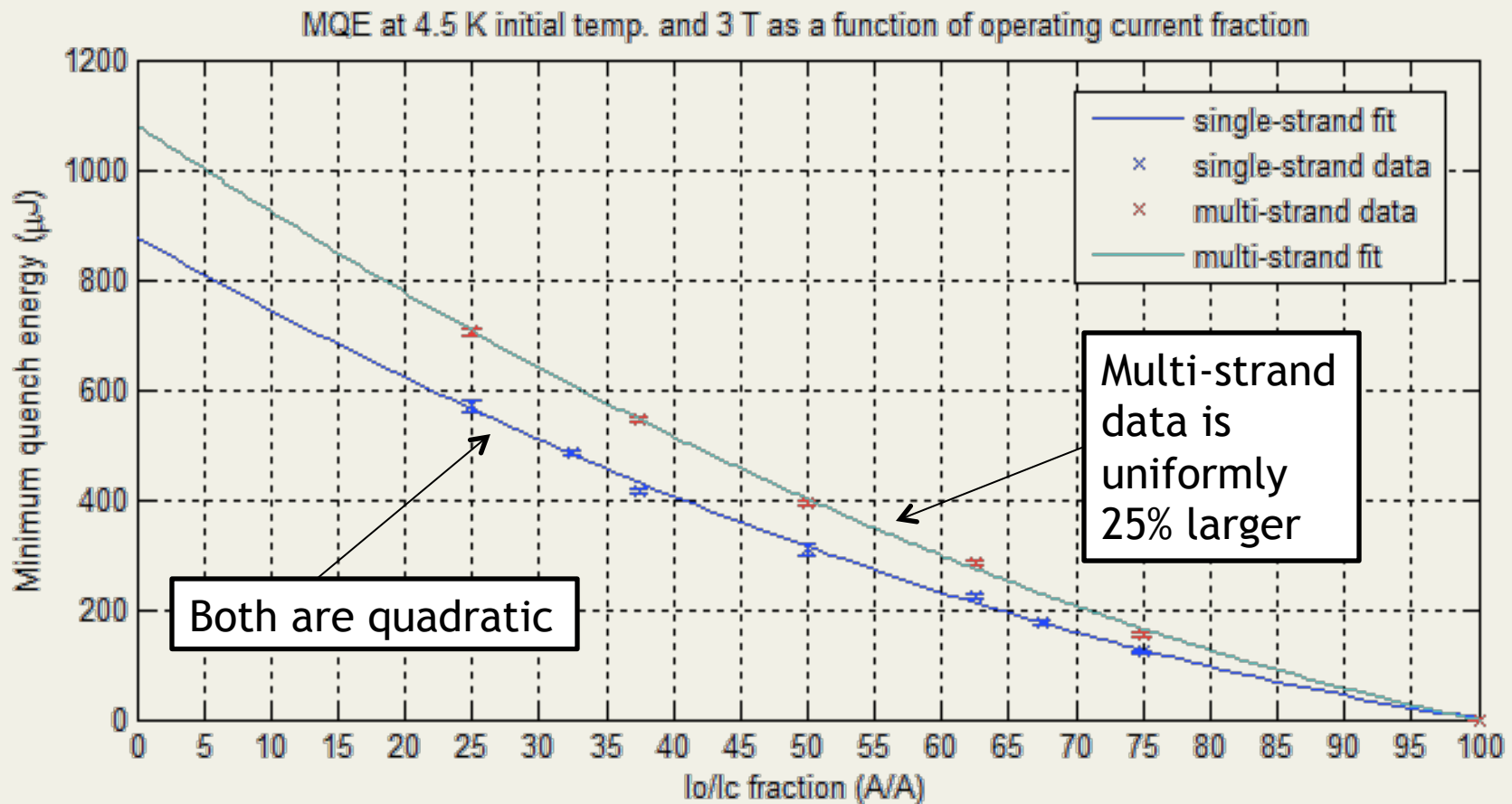
Example: single-strand case
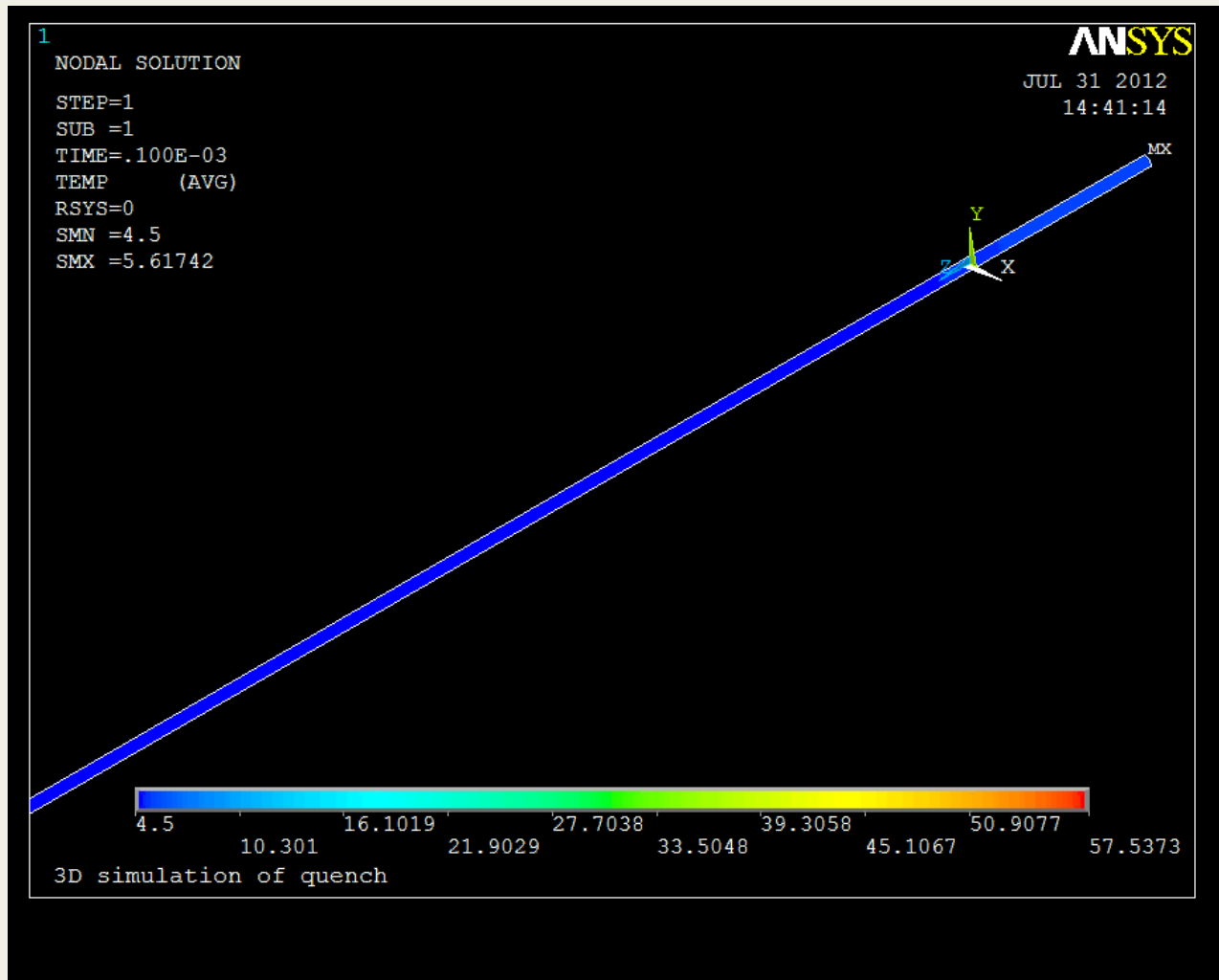
MIITS numerical prediction vs. ANSYS simulation

Simulated temperature vs. predicted temperature for a single strand at Io/Ic = 75%, 4.5 K initial temp. and 3 T vs. time

Simulated temperature quickly reaches MIITS-predicted value

Current sharing behavior

MQE Single & Multi-Strand Results

MQE at 4.5 K initial temp. and 3 T as a function of operating current fraction

Legend:
- single-strand fit
- × single-strand data
- × multi-strand data
- multi-strand fit

Multi-strand data is uniformly 25% larger

Both are quadratic

Conclusions

- A parametric, time-efficient 3-D FEA simulation was developed in ANSYS that simulates quench in superconducting magnets.

- A parametric MATLAB program was developed that predicts thermal behavior in a magnet quench.

- Thermal behavior appears to agree with MIITS prediction where it needs to.

- MQE curve values appear to behave correctly.

Conditions of first iteration:

- 1 timestep = 6 minutes
- Heavy code alteration was required to change minimal differences

Conditions of final iteration:

- 1 timestep = 15 seconds
- ~25 times faster!
- Minimal code alteration required to change entire geometry & operating conditions

Moving forward: what comes next?

- Experimental verification of results
- Measure stability margins for high-temperature superconductors and other expensive materials.
- Give superconducting materials testing a direction in which to perform studies.
- Optimize design of experiments requiring superconducting magnets: distribution efficiency, optimal insulation requirements, etc.

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Questions?